ACTIVE POWER FILTER CONNECTED TO A PHOTOVOLTAIC ARRAY

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Abstract: The existence of nonlinear loads in the utility has been increasing at an unprecedented pace in recent years. These types of loads draw non-sinusoidal currents from the mains, causing harmonic distortion. Active Power Filters have been intensively explored in the past decade. Various topologies and control schemes have been documented aiming at reducing the cost and improving the performance of the compensation system. Hybrid active filters inherit the efficiency of passive filters and the improved performance of active filters, and thus constitute a viable improved approach for harmonic compensation. This paper presents a single-phase hybrid active power filter connected to a photovoltaic array. The uniqueness of the proposed scheme is the fact that it improves the filtering performance of the conventional shunt active power filter, as well as simultaneously supplies the power from the photovoltaic array to the load. The compensation current reference estimation is based on the extension instantaneous reactive-power theorem. Simulation results obtained in laboratory confirmed the validity and effectiveness of the proposed scheme are presented.

Keywords: active power filter, power quality, passive filter, photovoltaic array, power electronics, total harmonic distortion (THD), Fast Fourier Transform (FFT).

1. INTRODUCTION

The power quality (PQ) problems in power utility distribution systems are not new, but only recently their effects have gained public awareness. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade, and there are indications that this trend will continue [1]. However the power electronics based equipments which include adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers, electronic ballasts are responsible for the rise in power quality related problems [1], [2]. These nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system. Harmonic currents produced by nonlinear loads are injected back into power distribution systems through the point of common coupling (PCC). As the harmonic currents pass through the line impedance of the system, harmonic voltages appear, causing distortion at the point of common coupling. Harmonics have a number of undesirable effects on the distribution system. They fall into two basic categories: short-term and long-term. Short-term effects are usually the most noticeable and are related to excessive voltage distortion. On the other hand, long-term effects often go undetected and are usually related to increased resistive losses or voltage stresses. In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading. These harmonic currents can also cause interferences with telecommunication lines and errors in metering devices. Because of the adverse effects that harmonics have on power quality, Standard has been developed to define a reasonable framework for harmonic control [3]. Its objective is to ensure steady-state harmonic limits that are acceptable by both electric utilities and their customers. Harmonic distortion in power distribution systems can be suppressed using two approaches namely, passive and active powering. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion. Although simple, the use passive elements do not always respond correctly to the dynamics of the power distribution systems. Over the years, these passive filters have developed to high level of sophistication. Some even tuned to bypass specific harmonic frequencies.

Conventional passive filters consist of inductance, capacitance, and resistance elements configured and tuned to control harmonics. Figure 1 shows common types of passive filters and their configurations.

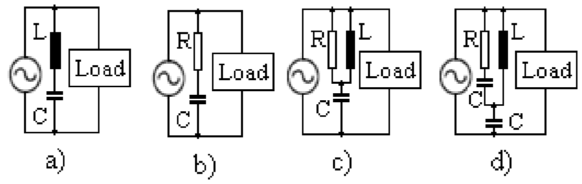

Figure 1. Common types of passive filters and their configurations: a) single-tuned; b) 1st-order High pass; c) 2nd-order High pass; d) 3rd-order High pass

The single-tuned "notch" filter is the most common and economical type of passive filter. The notch filter is connected in shunt with the power distribution system and is series-tuned to present low impedance to a particular harmonic current. Thus, harmonic currents are diverted from their normal flow path through the filter. Another popular type of passive filter is the high-pass filter (HPF). A high-pass filter will allow a large percentage of all harmonics above its corner frequency to pass through. High-pass filter typically takes on one of the three forms, as shown in Figure 1. The first-order, which is characterised by large power losses at fundamental frequency, is rarely used. The second-order high-pass filter is the simplest to apply while providing good filtering action and reduced fundamental frequency losses. The filtering performance of the third-order high-pass filter is superior to that of the second-order high-pass filter. However, it is found that the third-order high-pass filter is not commonly used for low-voltage or medium-voltage applications since the economic, complexity, and reliability factors do not justify them. Although simple and least expensive, the passive filter inherits several shortcomings. The filter components are very bulky because the harmonics that need to be suppressed are usually of the low order. Furthermore the compensation characteristics of these filters are influenced by the source impedance. As such, the filter design is heavily dependent on the power system in which it is connected to. Passive filters are known to cause resonance, thus affecting the stability of the power distribution systems. Frequency variation of the power distribution system and tolerances in components values affect the filtering characteristics. The size of the components become impractical if the frequency variation is large. As the regulatory requirements become more stringent, the passive filters might not be able to meet future revisions of a particular Standard. This may required a retrofit of new filters.

2. ACTIVE POWER FILTERS

Remarkable progress in power electronics had spurred interest in active power filters for harmonic distortion mitigation. The basic principle of active power filters is to utilise power electronics technologies to produce specific currents components that cancel the harmonic currents components caused by the nonlinear load. The information regarding the harmonic currents and other system variables are passed to the compensation current/voltage reference signal estimator.

The compensation reference signal from the estimator drives the overall system controller. This in turn provides the control for the gating signal generator. The output of the gating signal generator controls the power circuit via a suitable interface. Active power filters have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the active power filters performances are independent on the power distribution system properties. On the other hand, active power filters have some drawbacks. Active filtering is a relatively new technology, practically less than four decades old. There is still a need for further research and development to make this technology well established.

An unfavourable but inseparable feature of active power filter is the necessity of fast switching of high currents in the power circuit of the active power filter. This results in a high frequency noise that may cause an electromagnetic interference (EMI) in the power distribution systems. Active power filter can be connected in several power circuit configurations as illustrated in the block diagram shown in Figure 2.

In general, they are divided into three main categories, namely shunt APF, series APF and hybrid APF.

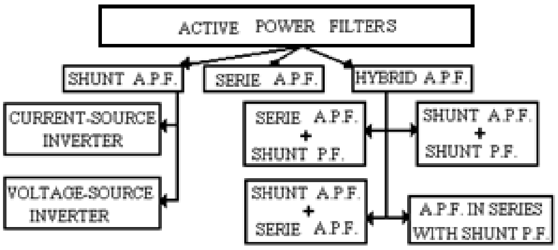

Figure 2. Subdivision of active power filter according to power circuit configurations

A shunt APF consists of a controllable voltage or current source. This is most important configuration and widely used in active filtering applications. The voltage source inverter (VSI) based shunt APF is by far the most common type used today, due to its well known topology and straight forward installation procedure.

The operation principle of series APF is based on isolation of the harmonics in between the nonlinear load and the source. This is obtained by the injection of harmonic voltages across the interfacing transformer. The injected harmonic voltages are added/ subtracted, to/from the source voltage to maintain a pure sinusoidal voltage waveform across the nonlinear load.

Technical limitations of conventional APFs mentioned above can be overcome with hybrid APF configurations. They are typically the combination of basic APFs and passive filters. Hybrid APFs, inheriting the advantages of both passive filters and APFs, provide improved performance and cost-effective solutions. The idea behind this scheme is to simultaneously reduce the switching noise and electromagnetic interference. The function of the hybrid APF can thus divided into two parts: the low-order harmonics are cancelled by the shunt APF, while the higher frequency harmonics are filtered by the passive HPF. This topology lends itself to retrofit applications with the existing shunt APF.

3. PHOTOVOLTAIC INTERACTIVE SHUNT ACTIVE POWER FILTER

The need to generate pollution-free energy has triggered considerable effort toward renewable energy (RE) system. Renewable energy sources such as sunlight, wind, flowing water, and biomass offer the promise of clean and abundant energy. Among the renewable energy sources, solar energy, is especially an attractive option. This useful energy is supplied in the form of DC power from photovoltaic arrays (PV) bathed in sunlight and converted into more convenient AC power through an inverter system. Efforts have been made to combine the shunt APF with photovoltaic system [4]. The photovoltaic arrays interactive shunt active power filter system can supply real power from the photovoltaic arrays to loads, and support reactive and harmonic power simultaneously to utilise its utmost installation capacity. This technology has many excellent features: it causes little environmental burden, it is of a modular type technology that can be easily expanded, and it is applicable almost everywhere.

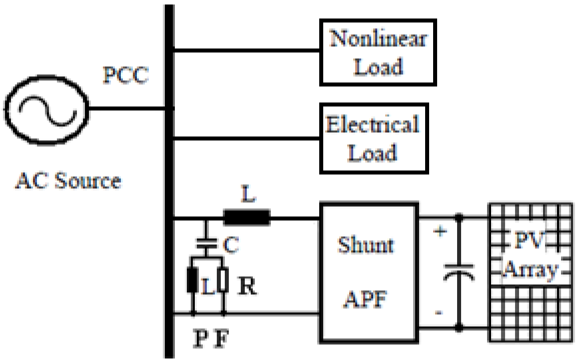

Figure 3. Configuration of photovoltaic interactive shunt active power filter system.

Figure 3 illustrates the configuration of a photovoltaic interactive shunt active power filter system. This scheme employs only one inverter to have the reactive power compensation, harmonic currents mitigation, and real power supply functions. In the day-time with intensive sunlight, the PV interactive shunt APF system brings all its functions into operation. At night and during no sunlight periods, the power required by the loads is received from the distribution system while the inverter system only provides reactive power compensation and filter harmonic currents. Thus, the utilisation level of the PV interactive shunt APF system is higher than the distribution line interactive PV inverter system. Although the research in combining APF and PV array is not new, it appears that no attempt has been made to combine a hybrid APF with PV array. The hybrid APF has been demonstrated to be an effective solution for harmonic mitigation. On the other hand, renewable energy (RE) sources, in particular solar energy has become feasible due to enormous research and development work being conducted over the years.

4. OPERATION PRINCIPLE OF THE PROPOSED HYBRID ACTIVE POWER FILTER

The operation principle of the proposed hybrid APF is illustrated in Figure 4.

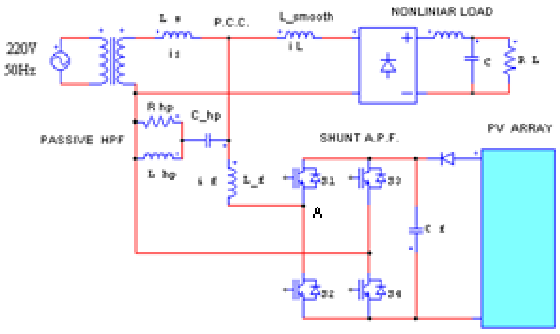

Figure 4. System configuration of the proposed hybrid APF.

It generates compensation current i_f equal to the reactive load current i_{Lq}, harmonic load current i_{Lh} and reactive HPF current $i_{hp,q}$. This compensation current is injected into the point of common coupling (PCC) through an interfacing inductor. The compensated source current i_s is desired to be sinusoidal and in phase with the source voltage v_s to yield a maximum power factor. In the proposed scheme, the low-order harmonics are compensated using the shunt APF, while the high-order harmonics are filtered by a passive high-pass filter (HPF). Since the aim in using the HPF is to improve the filtering performance of high-order harmonics, the HPF's resonant frequency can be tuned to frequency where the filtering performance of the shunt APF is impaired, i.e. over 1 kHz. In this way, the size of the HPF can be kept small. It is envisaged that this configuration is effective to improve the filtering performance of high-order harmonics. The size of interfacing inductor is a compromise between current control dynamic response and switching ripple. The current control dynamic response can be improved by using a small interfacing inductor. However, this would raise the switching ripple in the basic shunt APF. In the proposed hybrid APF, the resulting switching ripple is filtered by the HPF. In day-time where intensive sunlight is available, the proposed hybrid APF extracts power from the DC source that represents the PV array, providing additional PV current to the load. When the distribution source need to provide the peak power to the load, the energy provided by the PV array can alleviate the burden of distribution source. At night and during no sunlight periods, the power required by the load is delivered by the distribution source.

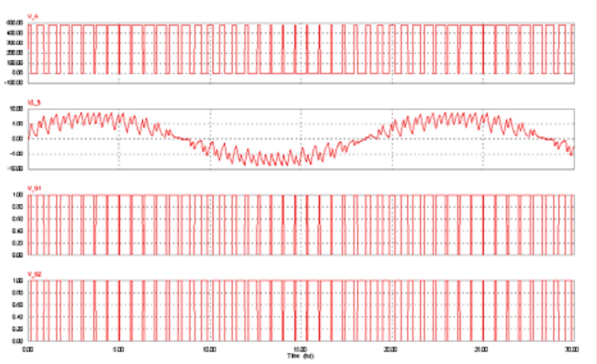

Figure 5. Simulation results –voltages and current waveforms.

The power circuit used in the proposed hybrid APF is a full-bridge VSI as shown in Figure 4. The VSI consists of four transistors, each connected to an antiparallel diode. The transistors are the insulated gate bipolar transistors (IGBTs). They are selected due to their superior performance characteristics, i.e. low forward voltage drop, fast switching times and high power handling capability. Gate drivers are needed to convert the gating signals to gate voltage that is suitable to the IGBTs (Figure 5). The logic inverters ensure that each IGBTs on the same leg complements each other. However, the finite switching times imply that during current commutation, the IGBTs in one leg (S1 and S2 or S3 and S4) may conduct at the switching instants. This will cause short circuit problem of the DC-bus capacitor C_f. Additional control logic in the gate drivers is needed to ensure the complete turn on and turn off processes of the IGBTs in one bridge leg. This is referred to as the blanking time, since both IGBTs have temporarily logic low gating signals.

5. HARMONIC DISTORTION ANALYSIS

The total harmonic distortion (THD) is the most common indicator to determine the quality of AC waveforms. Using the Fast

Fourier Transform (FFT), the harmonic spectrum of the source current under different compensation conditions are presented.

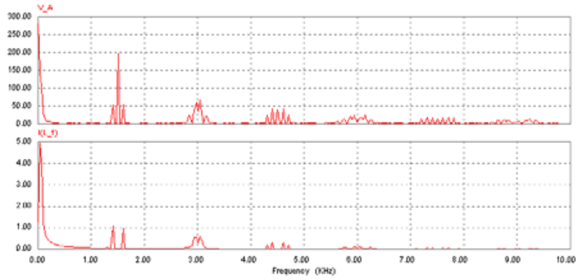

Figure 6. Spectrum of source current – simulation result

The spectrum of the source current without compensation is shown in Figure 6. From the spectra plot, it can be seen that the source current contains large amount of harmonic current components of frequencies below 2 kHz.

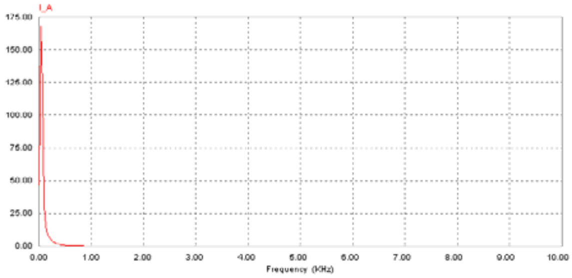

Figure 7. Spectrum of source current – simulation result

The spectrum of the source current with basic shunt APF compensation is shown in Figure 7. The basic shunt PF successfully filters the harmonic current components caused by the nonlinear load. Although the low frequency harmonic components (i.e. less than 2 kHz) are filtered significantly, appreciable amount of switching frequency harmonics still remain in the source current spectrum.

6. CONCLUSIONS

This paper has presented the development of a new variation of a single-phase hybrid APF topology, connected to a DC source that represents photovoltaic (PV) array. Firstly, the previous research works and related literatures are reviewed to give a better understanding of the related research area. Detailed description of the proposed hybrid APF is provided to offer an overview of the operation principle and its overall control system.

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